VALUE OF INCREASED USE OF SCHEDULED MAINTENANCE ON AIRCRAFT AVAILABILITY AND MAINTENANCE COST OF THE C-5

THESIS

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Captain, USAF

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Billy Webb

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Abstract

The C-5 consistently performs below its established mission capable rate of 75 percent. The purpose of this study was to investigate whether or not mission capable rates and maintenance costs can be improved by increased use of scheduled maintenance.

Nine C-5 components were studied. Availability and cost were compared when scheduled replacement occurred at ten, twenty, and thirty percent before their respective mean time between failure and actual failure times. Actual failure times were not available so they were generated using simulation. By replacing a component before its failure, an opportunity cost is incurred for the unused portion of its life span. The cost of replacing a component before failure was measured based on ten, twenty, and thirty percent of the cost of the component multiplied by the number of components replaced. Another cost factor is sending a MRT to remote sites to make repairs. The final cost is the opportunity cost of the aircraft being unavailable. The trade-off is the decreased cost of sending fewer MRTs and reduced C-5 downtime and associated opportunity cost, versus the increased cost of early component replacement.

The findings of this study suggest that the level of variance in the failure distribution of components will have an affect on the effectiveness of a preventive maintenance program. The use of preventive maintenance on components with a high variance in the failure distribution appears to have a negative effect on availability at a higher cost than with not using preventive maintenance. The use of preventive

maintenance on components with a moderate or small amount of variance in its failure distribution appears to be effective up to a point of diminishing return.

VALUE OF INCREASED USE OF SCHEDULED MAINTENANCE

ON AIRCRAFT AVAILABILITY AND MAINTENANCE COST OF THE C-5

I. Introduction

> *In February 1997, a C-5 aircraft was participating in the COBRA GOLD exercise in Thailand. A piece of hydraulic tubing ruptured. A replacement was manufactured at Travis AFB CA and shipped to Thailand. The tubing was not the correct shape, so a second was dispatched. The second piece of tubing was also the incorrect shape. The original broken tubing was sent back to Travis for the maintenance shop to replicate. Finally, the third attempt was successful. After over a week's worth of down time, the C-5 was now mission capable. A successful scheduled replacement preventive maintenance program could have helped avert this fiasco. (Weber, 1997)*

Background

The United States Air Force (USAF) C-5 Galaxy is a cargo transport aircraft designed to provide strategic airlift for deployment and supply of combat and support forces. Even with the fully operational status of the C-17 Globemaster III, the C-5 will provide the bulk of Air Mobility Command's (AMC) capability to transport outsized cargo into the future. There are 126 C-5 aircraft in the USAF inventory. The C-5A was added to the USAF inventory in 1969 with 50 additional C-5Bs added from 1986-1989. Both models have a planned structural service life of 50,000 hours (HQ AMC, 1998a:5-28-5-29). This projected service life should be sufficient to provide capability until 2020. In an address to the Air Force Association, General Walter Kross, Commander, Air Mobility Command and United States Transportation Command, stated that the C-5 still possesses 80 percent of its structural life remaining (Kross, 1997:3).

By 2007, all 266 C-141s will retire and 120 C-17s will be activated. This decrease of 146 "T-tails" creates a situation of decreased flexibility in responding to multiple mission taskings. Thus, there exists a strong need for the C-17 to be successful and for the reliability of the C-5 to be greatly improved. Increasing the C-5s reliability is absolutely necessary to achieve the Air Force's strategy of "Rapid Global Mobility" (HQ AMC, 1998a:2-29).

The C-5 has historically experienced a low mission capable rate. Mission capable is defined as the aircraft is available and ready for the assignment of a mission. The target mission capable rate for the C-5 is 75 percent. This means that 75 percent of the C-5 fleet, minus those in depot maintenance, should be available when given a mission tasking. The mission capable rate for the C-5 was 63 percent for CY97, lower than comparable transport aircraft during the same period (HQ AMC, 1998b:n. pag.). See table 1 for comparison.

Table 1
Comparison of Comparable Mission Capable Rates

Aircraft	Mission Capable Rate (%)
C-5	63
C-141	71
KC-10	80
KC-135	73

Source: (HQ AMC, 1998b:n. pag.)

The C-5 currently has the highest cost per flying hour of any AMC weapon system (Davis, 1998:n. pag.). The flying hour cost is based on three costs: aviation fuel (AVPOL); Material Support Division (MSD), which is mainly reparables; and General

Support Division (GSD), consumables. Both MSD and GSD are divisions of the Supply Management Activity Group of the Air Force Working Capital Fund. See table 2 for comparison of FY98 AMC flying hour rates.

Table 2
FY98 AMC Flying Hour (Variable) Funded Rates

Aircraft	AVPOL	MSD	GSD	Total
C-5[a]	$3,359	$3,169	$879	$7,407
C-141[a]	$1,913	$903	$440	$3,256
KC-10[b]	$2,427	$1,900[c]	$43	$4,370
KC-135[b]	$1,454	$445	$197	$2,096

Source: (Davis, 1998:n. pag.)
[a] C-5/C-141 source: FY98 funded rates from the budget office of the Secretary of the Air Force (SAF/FMB)
[b] KC-10/KC-135 source: FY98 Transportation Working Capital Fund budgeted rates
[c] KC-135 maintenance is performed through contracted logistics support, therefore the MSD cost is based on a flying hour adjustment factor.

The C-5 is programmed for many new modifications that, once fully funded, should be completed by fiscal year 2004. The modifications include changes to nearly every major system, including avionics, hydraulics, engines, and defensive systems. The 1998 Air Mobility Master Plan contains a complete list of modifications and descriptions (HQ AMC, 1998a:5-30-5-33). These modifications are expected to improve the C-5's mission capable and mission availability rates. Until the modifications are completed, AMC is actively managing the C-5 Capital Improvement Plan (CIP). The C-5 CIP is AMC's roadmap for improving the C-5. The CIP considers upgrades, repairs, and modifications. The CIP has four objectives: restore aircraft reliability and maintainability, maintain structural and system integrity, reduce cost of ownership, and increase operational capability (HQ AMC, 1998a:7).

Considering the C-5 has a vast amount of its life span still ahead, it seems prudent to attempt to improve the C-5's mission capable and mission reliability rates, while controlling cost, by means other than modification and modernization, as well. The use of scheduled replacement for components that have low mean time between failure may increase the C-5's availability and lower maintenance costs. Presently, the repair or replacement of some components is based on time or utilization. However, this is not the case for all components. Most components are repaired or replaced on a "fly-to-fail" basis, meaning that these components are not replaced until actual failure. Therefore, failure is not predicted for these components. When these components do fail, the results often occur during flight preparation causing mission failure, or at best, mission delay. These failures can also occur at remote sites without an in-place maintenance function, requiring the dispatch of a maintenance repair team (MRT) to repair the aircraft at additional cost. Given the C-5's reputation for poor reliability, this is an obvious problem. Consequently, careful scheduling of maintenance actions results in the requirement of fewer MRTs. By utilizing more scheduled maintenance, components' replacement based on their respective mean times between failure can be programmed to coincide with other planned maintenance actions, thereby increasing mission reliability and mission capable rates, while reducing total maintenance costs.

Mission capable rate is not a perfect measure of the C-5's ability to meet mission requirements. An aircraft classified as mission capable could break down on pre-flight or take-off, rendering it not mission capable. However, if components with a low mean time between failure are replaced before failure, the probability of unexpected failure should be reduced.

Problem Statement

The C-5 consistently performs below its established mission capable rate of 75 percent. The purpose of this study is to investigate whether or not mission capable rates and maintenance costs can be improved by increased use of scheduled maintenance.

Methodology

Nine components that are currently replaced at failure. HQ AMC/LGQ provided the mean time between failure and the mean time to repair for each component through the G081 computer system. HQ AMC/LGQ also provided the cost of each component. The G081 computer system, officially known as the Core Automated Maintenance System for Mobility, is an AMC computer system which automates the scheduling and tracking of aircraft maintenance for most AMC aircraft (HQ AMC, 1997d:1).

Availability and cost were compared between replacing the nine components at ten, twenty, and thirty percent before their mean time between failure and at their actual failure time. Actual failure times were not available so they were generated using simulation. By replacing a component before its failure, an opportunity cost is incurred for the unused portion of its life span. The cost of replacing a component before failure was measured based on ten, twenty, and thirty percent of the cost of the component multiplied by the number of components replaced. Another cost factor is sending a MRT to remote sites to make repairs. This additional maintenance cost was captured by computing a percentage of C-5 flights that require a MRT and the average cost of deploying a MRT. The final cost is the opportunity cost of the aircraft being unavailable. The USAF charges $12,605 per flying hour to Department of Defense customers for C-5

missions (HQ AMC, 1998c:9). For purposes of this analysis, this dollar figure will be used as an opportunity cost per hour when the aircraft is unavailable. The trade-off is the decreased cost of sending fewer MRTs and reduced C-5 downtime and associated opportunity cost, versus the increased cost of early component replacement.

Although nine specific components were used, they really only useful in this study as representations of actual mean failure times, repair times, and costs. The components were chosen because they have low mean times between to failure. In this study, the components themselves are not as important as their respective failure, repair, and cost characteristics.

Research Questions

By using a scheduled replacement maintenance approach for the nine components, mission capable rates should remain the same or increase. Pipeline costs will remain the same or decrease because forecasting should be more accurate. The worst that could happen would be status quo. There are three research questions:

1) By using a scheduled replacement maintenance approach for the nine components, will mission capable rate increase?

2) By using a scheduled replacement maintenance approach for the nine components, will maintenance cost decrease?

3) What is the cost comparison of the changes in mission capable rate and maintenance cost?

II. Literature Review

Overview

Increasing the availability and reliability of the C-5 is an absolutely necessary objective of the United States Air Force. There is a projected deficit in supporting the 49.7 million ton miles per day (MTM/D) cargo airlift requirement as established by the Department of Defense's Mobility Requirements Study Bottom-Up Review Update (HQ AMC, 1998a:2-29). The future deactivation of the 266 aircraft in the C-141 fleet and the procurement of only 120 C-17 aircraft limit AMC's flexibility in supporting multiple mission taskings. AMC has requested funding for an additional 120 C-17 aircraft to help over come this shortage. Improving C-5 availability and reliability is imperative to meeting the 49.7 MTM/D objective with or without the additional C-17s. Methods of improving the C-5 support two of the six AMC air mobility strategies. The strategies are "enhance mission capability through modernization" and "increase efficiency and effectiveness" (HQ AMC, 1998a:1-4-1-5). Increased use of scheduled maintenance should support these strategies by increasing the C-5's availability and reliability and decreasing cost by decreasing the number of unplanned and unexpected failures.

Maintenance

Maintenance is defined as the process of returning a failed system to operational status or attempting to preempt expected failures with preventive measures, while endeavoring to maintain an acceptable operational level. Maintenance can be separated into two broad categories: corrective maintenance and preventive maintenance. Corrective maintenance is "the unscheduled actions initiated as a result of system failure

(or perceived failure) that are necessary to restore a system to its expected or required level of performance" (Blanchard, et al., 1995:97). Preventive maintenance is "the scheduled actions necessary to retain a system at a specified level of performance" (Blanchard, et al., 1995:97). Corrective Maintenance is reactive in nature while preventive maintenance uses scheduled downtime to perform a predetermined list of maintenance actions.

Corrective Maintenance. Corrective maintenance action is not planned as it occurs as a result of an unscheduled failure. The amount of corrective maintenance required is based in the inherent reliability of the subsystems, excluding damage from accidents or combat. There are four basic steps to the corrective maintenance cycle. The first is the observation of system failure. The second step is to isolate the source of the failure. The third step is to repair the failure. Last, verify that the failure has been eliminated (Moss, 1985:51).

Preventive Maintenance. Preventive maintenance is limited to actions that serve to prevent or delay the occurrence of anticipated failures. It deals primarily with wear out type failures. Thus, preventive maintenance extends the system reliability beyond the mean time between failure that would be expected if every component is allowed to operate until failure. There are five types of preventive maintenance. *Servicing* tasks are performed to maintain equipment in proper operating condition. These tasks include replenishment of consumables, such as fuel, minor adjustments, cleaning of surfaces which are subject to contamination, and replacement of filters. *Condition-monitoring* maintenance observes the system's operation to detect conditions that suggest an approaching failure or a failure that has already occurred. *Condition assessment* is a

scheduled inspection of the physical condition of components that are subject to wear or other forms of deterioration. Methods of condition assessment include nondestructive and visual tests. If certain conditions are met, then an "on-condition remedial action" is completed. *Verification of Hidden Functions* is the evaluation of functions not utilized during normal operation, such as emergency or redundant functions, and, therefore, are not a part of condition-monitoring. *Scheduled replacement* is utilized under three conditions: when a failure of the component would endanger personnel or equipment or reduce the availability of the system below an acceptable level, when the failure mode is not suitable for condition assessment, and when the life span of the component is significantly less than the intended operating life of the system (Moss, 1985:48-50). Scheduled replacement is the maintenance technique under study in this research effort.

Air Force Instruction 21-101 dictates the Air Force level guidance for the management of a safe and effective aircraft maintenance program. Each aircraft has a maintenance program specific to its operational mission. The maintenance program considers such factors as mission requirements, transportation limitations, component reliability, and special training requirements. All of the maintenance programs contain a preventive maintenance schedule designed with specific inspection and servicing requirements. "By following [the preventive maintenance] program, aircraft components will operate for a longer time and contribute to the goal of increasing aircraft availability" (HQ USAF, 1997:5).

The economy and effectiveness of preventive maintenance is dependent on failure distributions of the components and, subsequently, the failure distribution of the system. Generally speaking, if a component has a decreasing failure rate (meaning that a

component's failure rate decreases over time), then replacement of the component will increase the probability of a failure. If a component has an increasing failure rate (meaning that the component's failure rate increases over time), then replacement at anytime will improve the reliability of the system. If a component has a constant failure rate (meaning that the component's failure rate does not change over time), then replacement will have no effect on the reliability of the system. However, if a component has an increasing failure rate and a failure-free life greater than its scheduled replacement interval, the probability of failure is zero (O'Connor, 1991:324). See figure 1 for a graphic representation of the relationship between reliability and scheduled replacement.

The above relationship assumes that replacement action does not induce a different component failure (O'Connor, 1991:324). This cannot be assumed without question. If the replacement of one component increases the probability of another component's failure, then the better course of action may be to wait and replace the component at failure.

Availability

Availability is "the probability that a component or system is performing its required function at a given point in time when used under stated operating conditions" (Ebeling, 1997:6). This measure is comparable to the military's mission capable rate. The achieved availability is based on the mean time between maintenance (MTBM) which includes both unscheduled and scheduled maintenance, and the mean system downtime which is the average downtime including scheduled maintenance but excluding supply or maintenance delay times. Operational availability is similar to achieved

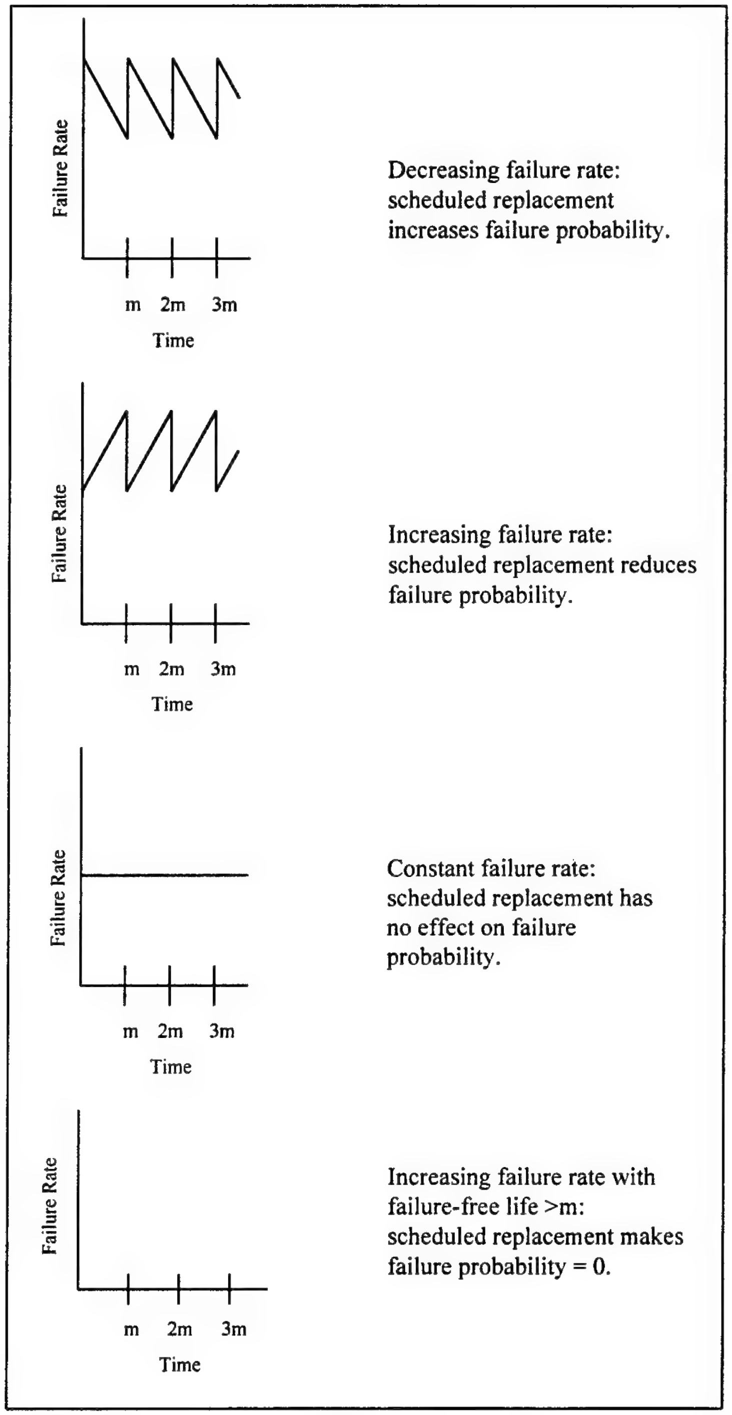

Figure 1
Relationship Between Reliability and Scheduled Replacement
Source: (O'Connor, 1991:325)

availability, but it also includes supply and maintenance delays in the unscheduled downtime. Inherent availability is based on the mean time between failure (MTBF) and the mean time to repair (MTTR). The relationship is illustrated in equation (1) (Ebeling, 1997:255-257). For purposes of this study, maintenance delay time associated with sending a MRT will be combined with the MTTR in the inherent availability definition which creates more of an operational reliability.

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

where

A = availability

MTBF = mean time between failure

MTTR = mean time to repair

Cost

Improving the reliability of the C-5 will lead to increased combat capability by improving the availability rate and reducing support costs by requiring fewer mobile repair teams. The cost of deploying a MRT is limited to per diem, transportation, and billeting associating with supporting the members of the MRT. According to HQ AMC/LGQ, in FY98 (up to 21 July 1998), 112 MRTs were deployed from Travis AFB in support of broken C-5 aircraft. The average cost of these MRTs was $2,000.

Preventive maintenance is cost effective only when it eliminates the more costly aspects of corrective maintenance (Moss, 1985:48). For the scheduled replacement policy suggested by this research effort, the cost of corrective maintenance would include the cost of lost availability. The Air Force charges $12,605 per flying hour to

Department of Defense customers for C-5 missions (HQ AMC, 1998c:9). This can be used as the average opportunity cost per hour when the C-5 is unavailable and subsequently, as the cost of lost availability.

A 1997 Government Accounting Office (GAO) report stated that the military's planned investment in the modification and procurement of aircraft is not achievable within foreseeable budgets. The GAO goes on to state that the Depart of Defense (DoD) believes that sufficient funds will be available because beginning in FY 2002 DoD budgets will increase in real terms and savings will be realized through acquisition reform and the downsizing of infrastructure. The GAO believes that these assumptions are overly optimistic (GAO, 1997:2). Suffice it to say that budget dollars will become increasingly harder to obtain, especially for expensive aircraft procurement and modification. The more prudent option is to modify our processes where possible to accomplish cost savings and improve the availability of our aircraft weapon systems. Plus, these savings could be applied to other items on the budget which have not been fully funded.

III. Methodology

Overview

The nine components studied are currently replaced at failure. The mean time between failure and the mean time to repair for each component was obtained from HQ AMC/LGQ through the G081 computer system. HQ AMC/LGQ generated a G081 C-5 Work Unit Code (WUC) Summary Report that listed the relevant information for all C-5 work unit codes including the mean time between failure and mean time to repair. The 11000 (airframe) and 23000 (engine) series WUCs were deleted because of the extensive review they are receiving from AMC. The data was then sorted by mean time between failure. Every fifth component was selected until nine were chosen. Every fifth component was chosen (as opposed to the first nine) so that the mean failure times were not too close (for purposes of the simulation). HQ AMC/LGQ provided the cost of the nine components as well. See table 3 for list of the chosen components.

Table 3
Nine C-5 Components and Work Unit Codes

WUC	MTBF	MTTR	Cost ($)
12CAF	189.42	10.87	40,000.00
13AUG	110.04	1.93	27.57
13AUL	110.04	2.6	180.00
44DAA	151.77	1.51	650.00
44DAD	77.91	1.28	0.30
45JAQ	120.75	1.65	85.00
45LAA	121.94	3.36	64,983.12
51ACO	137.48	2.32	43,162.26
51AFA	140.19	2.83	17,000.00

Source: HQ AMC/LGQ

HQ AMC/LGQ provided the number and cost of Maintenance Repair Teams (MRT) deployed by the 60th Aircraft Generation Squadron and 60th Equipment Maintenance Squadron of Travis Air Force Base (AFB) and the number of Travis AFB based C-5 flights for FY98 (through 21 July 1998). There were 112 MRT deployments and 1939 C-5 flights. On average, 5.8 percent required the deployment of a MRT. The average cost of the MRTs was $2,000. See appendix A for details of this information.

A cost comparison was made between replacing the nine components at 10, 20, and 30 percent before their mean failure time and replacing them at their actual failure time. Actual failure times were not available so they were generated using simulation.

Simulation

Background. A simulation is a problem solving technique using a simplification of a real word system or process to study some behavior. A system is some sector of reality that is of interest. A system's boundary must be defined. The boundary may be physical or may be thought of in terms of cause and effect. If some factor external to the system completely controls the behavior of the system, then the system has not been properly defined. If the factor has only limited impact on the system, then the system definition can be altered, the factor can be ignored, or the factor can be treated as a system input (Pritsker, O'Reilly, and LaVal, 1997:2-3).

A simulation model is used to observe the behavior of a system. The model is based on a set of assumptions expressed through "mathematical, logical, or symbolic relationships between ... entities, or objects of interest, of the system" (Banks, Carson, and Nelson, 1996:3). A simulation model can be used to study the effects of a series of

"what-if" questions on a real-word system. In most cases, it is preferable to explore the potential effects of changes to a complex system through simulation rather than by experimenting with the real world system (Banks, Carson, and Nelson, 1996:4).

The simulation model needs to be verified and validated to ensure the accuracy of the decisions based on the results of the simulation effort. Verification and validation should be an integral part of the model building process. "Verification is concerned with building the model right ... [v]alidation is concerned with building the right model" (Banks, Carson, and Nelson, 1996:399-400). Verification deals with whether or not the model is accurately implemented in the computer. Validation deals with whether or not the model accurately reflects the real world system it is intended to simulate.

Simulation models were built using SLAMSYSTEM Version 4.5. The "original model" is a simulation of the current "fly-to-failure" approach without preventive maintenance for the nine components. The "scheduled replacement model" is a simulation of the proposed scheduled replacement preventive maintenance policy for the nine components. The system is a C-5 aircraft.

Original Model. The "original model" is straightforward. Each branch of the simulation is a method of failure, namely one of the nine components, of the system. Each branch is a duplicate of the other nine. The only difference is the respective failure distributions and mean time to repair. See figure 2 for a graphic representation of one branch of the "original model". An entity is created at time zero and continuously looped through the branch. The entity is the component. Through the course of the simulation the component is utilized, fails, and is replaced in a continuous loop. For each iteration,

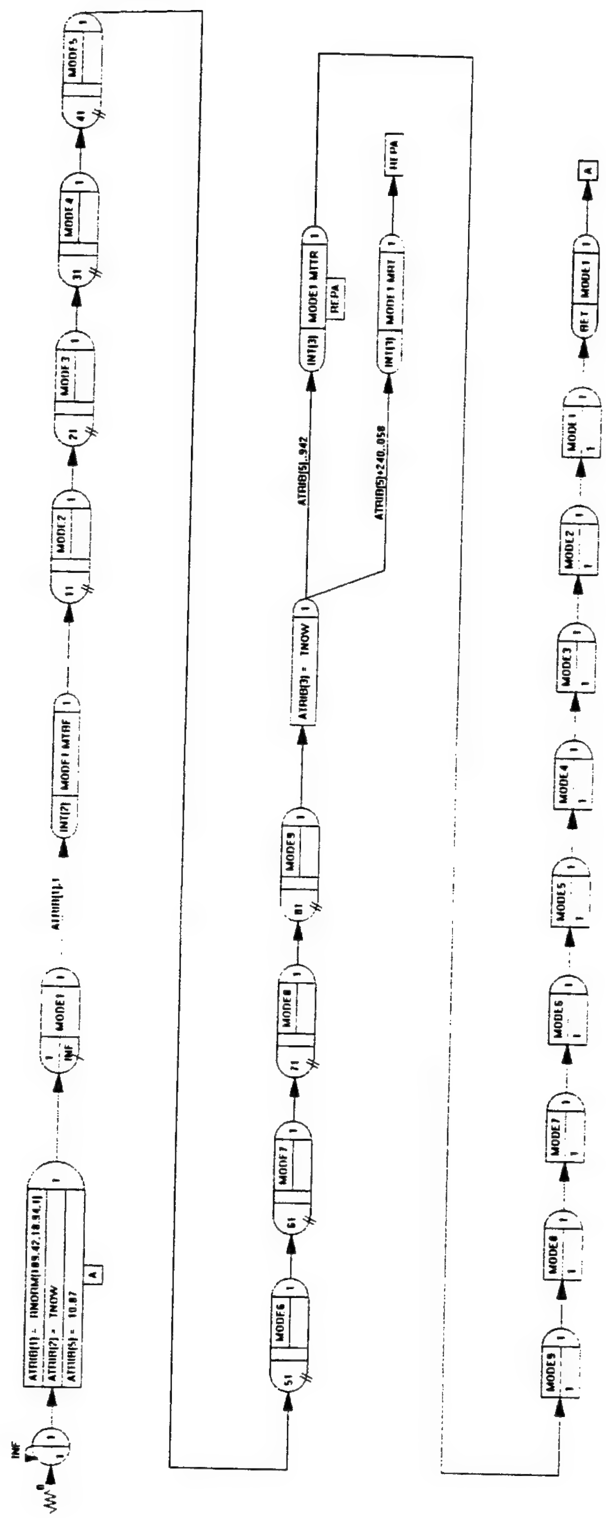

Figure 2
One Branch of the Original Model

the components are assigned four specific attributes. Attribute one is the time the entity will fail based on the given distribution. Attribute two is assigned the current time and is used to measure the times between failure to ensure that the simulated mean time between failure is the same as the given mean time between failure. Attribute three is assigned the current time and is used to measure the times to repair to ensure that the simulated mean time to repair is the same as the given mean time to repair. Attribute four is the amount of time it will take to replace the component (mean time to repair the component). When a component reaches its failure time, as assigned to attribute one, all other component failure times are preempted. Each component is depicted as a resource and as the time to fail accumulates, up to the assigned failure time, the resource is utilized. Once a failure of one component occurs, the other nine resources are preempted and go into a "time out" mode until the failed component is repaired. The logic is that while the C-5 is in a non-operational status due to the failure of a component, time will not continue to accumulate on the other components. Therefore, the respective accumulated times to failure are preempted until the failed component is replaced, and after the repair, the resources are freed and time begins again where it stopped until the next component reaches its assigned failure time. MRTs will be generated for 5.8 percent of the failures as discussed previously.

Scheduled Replacement Model. The "scheduled replacement model" is a simulation of the proposed scheduled replacement policy. This model is similar to the "original model". Each branch of the simulation is a method of failure of the system. Each branch is a duplicate of the other eight except for the different failure distributions and the repair times. See figure 3 for a graphic representation of one branch of the

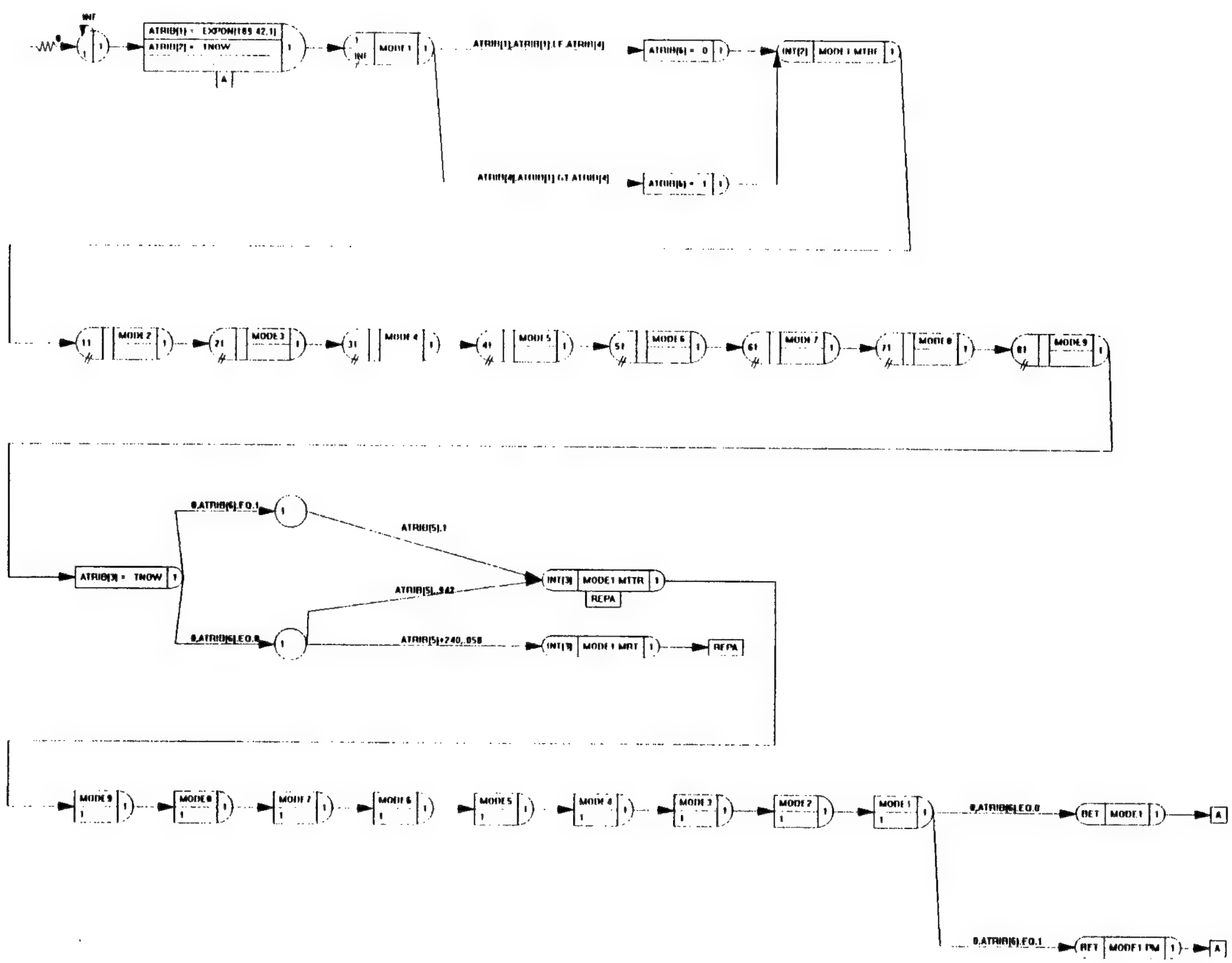

Figure 3
One Branch of the Scheduled Replacement Model

"scheduled replacement model". An entity is created at time zero and continuously looped through the branch. The entity is the component. Through the course of the simulation the component is utilized, fails, and is replaced in a continuous loop. For each iteration on each branch, the components are assigned five specific attributes. Attribute one is the time the entity will fail based on the given distribution. Attribute two is assigned the current time and is used to measure the times to failure to ensure that the simulated mean time between failure is the same as the given mean time between failure. Attribute three is assigned the current time and is used to measure the times to repair to ensure that the simulated mean time to repair is the same as the given mean time to repair. Attribute four is the time at which the scheduled replacement will be performed. Attribute five is the amount of time it will take to replace the component (mean time to repair the component). Attribute six is assigned the value of zero or one depending on whether the component was replaced through scheduled replacement or if it failed before the scheduled time. This will allow for the collection of the number of preventive maintenance and corrective maintenance actions. MRTs will only be required if the failure occurs before the scheduled time. The simulation runs basically the same as the "original model" except that each entity travels a different path on its respective branch based on the comparison of attribute one, assigned failure time, and attribute four, time of scheduled replacement. If the failure time is greater than the scheduled replacement time, meaning that the component did not fail before it was replaced, then the entity travels a particular path. If the failure time is less than the time of scheduled replacement, meaning that the component failed before the scheduled replacement time, then the entity will travel another path and 5.8 percent will require a MRT. This allows for the

collection of the number of component replacements (preventive maintenance) for opportunity cost in the former and the number of unexpected component failures (corrective maintenance) in the latter. Scheduled replacement occurred at 10, 20, and 30 percent before the mean. The mean was not utilized in an effort to minimize the number of unexpected component failures.

Verification and Validation. The common random numbers technique was used to ensure that the only difference between the 12 simulation models was the failure distribution and type of preventive maintenance. Using common random numbers means that identical random number streams were used in both simulations where possible. This technique will "usually reduce the variance of the estimated difference of the performance measures and thus can provide, for a given sample size, more precise estimates of the mean difference than can independent sampling" (Banks, Carson, and Nelson, 1996:475).

Efforts were made by the researcher to verify that the model was accurately implemented in the computer. SLAMSYSTEM Version 4.5 uses a graphic interface to build the simulation model, which allows for a flow chart type of documentation and easy understanding of the structure of the model. All variables collect the same information for each branch of the model and have been documented in table 4. Output statistics were reviewed to ensure that input parameters had not been entered incorrectly. The output statistics included the mean time between failure and mean time to repair that resulted from the simulations.

Table 4
Description of Simulation Collection Variables

Name of Variable*	Description
Model MTBF	mean time between failure of component 1
Model MTTR	mean time to repair component 1 including delay time caused by MRTs
Model MRT	Number of deployed MRTs as a result of component 1 failure
Model	Number of component 1 corrective maintenance actions
Model PM	Number of component 1 preventive maintenance actions

*note: In the models, each variable name corresponds to its respective component number.

Validation of the simulation model in comparison to the real word system is more difficult. Only the mean time between failure and the mean time to repair of the components under study were used as actual failure and repair times were unavailable. In an effort to determine the robustness of the simulation model, availability was compared with three different distributions to model failure times: a normal distribution to demonstrate the effects of a mean with a small variance, an Erlang distribution to demonstrate the effects of a mean with a moderate variance, and an exponential distribution to demonstrate the effects of a mean with a large variance.

The standard deviation of each component's failure distribution was not available. Standard deviations were estimated using the coefficient of variation. The coefficient of variation is defined as the standard deviation divided by the mean giving the standard deviation as a proportion of the mean (McClave and Benson, 1994:265). For the normal distribution, the coefficient of variance used was .1 (low variance). For the Erlang distribution, the coefficient of variance used was .5 (moderate variance). For the exponential distribution, the effective coefficient of variance used was 1 (high variance).

Standard deviations were not calculated for the exponential distribution because they were not required for the simulation program.

In all, there were twelve models, four for each distribution (scheduled replacement at 1σ, 2σ, and 3σ below the mean and with no preventive maintenance). Each simulation continued for 49,630 hours, which is the amount of time upon which the given means were based. The models were simulated for 5,000, 10,000, and 15,000 hours to determine when the model reached steady-state. Steady-state refers to a time during the simulation where the long run properties of the system are no longer influenced by the initial conditions (at time zero) of the model (Banks, Carson, and Nelson, 1996:436). The models reached steady-state at 15,000 hours. The models' data collection variables were cleared at 15,000 hours so as not to be influenced by the initial conditions. The models were then run for the 49,630 hours. A pilot test of 15 replications with each of the three failure distributions was accomplished. A t-test was performed to see if there was a statistical difference in the availability and cost calculated through the simulation models. Fifteen additional replications were performed with the exponential distribution.

The assumptions of the model are as follows: only one component will fail at a time (components are assumed to be independent, no cascading types of failures) and after component is repaired it is in an as-good-as-new condition.

Availability

The system availability was calculated for each replication. The system availability equation is basically the same as the availability equation given in chapter II.

The modified form is given in equation (2) with parameters defined in equations (3) and (4) (Ebeling, 1997:202).

$$A_{sys} = \frac{MTBF_{sys}}{MTBF_{sys} + MTTR_{sys}} \tag{2}$$

$$MTBF_{sys} = \frac{Total\ Number\ of\ Failures}{TotalHours} \tag{3}$$

$$MTTR_{sys} = \frac{\sum_{i=1}^{9} f_i MTTR_i}{\sum_{i=1}^{9} f_i} \tag{4}$$

where

A_{sys} = system availability
$MTBF_{sys}$ = system mean time between failure
$MTTR_{sys}$ = system mean time to repair
$MTTR_i$ = meant time to repair component i
f_i = the average number of failures of component i

Cost

The cost of the current system is calculated as the sum of cost of lost aircraft availability, cost of corrective maintenance, and the cost of MRTs. As discussed previously, the cost of lost aircraft availability is $12,605 per hour multiplied by the number of hours not available. The number of hours not available is one minus the availability multiplied by the total number of flying hours. For example, if the availability is 75 percent and the total number of flying hours is 40,000, then the number of hours not available would be 10,000 (25 percent * 40,000 hours). The cost of corrective maintenance is each respective component's cost multiplied by the number of

components required during the period. Labor cost is not taken into consideration. The MRT cost was computed by multiplying the number of simulated MRTs by the average cost of $2,000 (as discussed above).

The cost of the scheduled replacement policy is calculated as the sum of cost of lost aircraft availability, the cost of replacing components early, cost of corrective maintenance, and the cost of MRTs. The same definitions are used for this model except the cost of replacing components early is added. By replacing a component before its failure, an opportunity cost is incurred for the unutilized portion of its life span. The number of components that were replaced before failure multiplied by 10, 20, and 30 percent, respectively, of their specific cost were added together to get the opportunity cost of replacing components early.

Statistical Analysis

Two-tailed paired difference tests were used in the six comparisons for each distribution to determine if a difference existed between the respective cost and availability calculations. The assumptions of the paired difference test are normal frequency distribution of differences and randomness. The null hypothesis is that the difference in the means is zero. The alternate hypothesis is that there is a difference in the means (McClave and Benson, 1996:424). By using common random numbers in the simulation, the differences will be random but not independent.

The Bonferroni Procedure was used to ensure an overall level of significance of .1 or, equivalently, an overall confidence level of 90 percent. Using this procedure, the level of significance for each comparison is the overall significance level divided by the

number of comparisons (McClave and Benson, 1996:867). In this case, the level of significance for each of the six comparisons in each of the three distributions is .016 (.1/6).

IV. Results and Analysis

Overview

The results and analysis of the 12 simulations are presented in this chapter. Within each of the three distributions used, exponential, Erlang, and normal, cost and availability associated with replacing components 10, 20, and 30 percent before the mean time between failure were compared to replacement at failure (no preventive maintenance) and, when statistically significant, to each other. There was a total of six comparisons within each distribution. Two-tailed paired difference tests were used in the six comparisons for each distribution to determine if a difference existed between the respective cost and availability calculations. The Bonferroni Procedure was used to ensure an overall level of significance of .1 or, equivalently, an overall confidence level of 90 percent. In this case, the level of significance for each of the six comparisons in each of the three distributions is .016 (.1/6).

Exponential Distribution

A summary of the simulation results for the four exponential distribution models is provided in appendix B. The averages for the 30 replications of each of the four models are reported in table 5. The comparison of availability to cost implies that when component failure distributions have high a high amount of variability, such as the exponential distribution, scheduled replacement before the mean failure time tends to increase maintenance cost and decrease availability. This agrees with the theoretical *memorylessness* property of the exponential distribution (Banks, Carson, and Nelson, 1996:205).

Table 5
Exponential Distribution Overall Averages

	Availability (%)	Cost ($)
No PM	64.43	25,064,369
10 percent	63.50	26,764,168
20 percent	62.86	29,098,724
30 percent	62.93	31,787,372

Availability paired difference tests results are reported in table 6 and cost paired difference tests results are reported in table 7.

Table 6
T-values for the Exponential Distribution Paired Difference Tests of Availability

	10 percent	20 percent	30 percent	No PM
10 percent	---	1.03	6.18*	-6.50*
20 percent	---	---	-0.12	-2.42
30 percent	---	---	---	-11.42*

* Significant at the overall significance level of .1 (n = 30, df = 29, and critical t-value = 2.558)

Table 7
T-values for the Exponential Distribution Paired Difference Tests of Cost

	10 percent	20 percent	30 percent	No PM
10 percent	---	-5.15*	-12.54*	4.99*
20 percent	---	---	-6.01*	9.59*
30 percent	---	---	---	17.39*

* Significant at the overall significance level of .1 (n = 30, df = 29, and critical t-value = 2.558)

Ten percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 10 percent below the

mean failure time and the actual failure time was a 1.44 percent ((64.43%-63.50%)/64.43) decrease and the percentage change in cost was a 6.78 percent ((25,064,369-26,764,168)/ 25,064,369) increase. The t-value for the comparison of availability of 10 percent below the mean versus no preventive maintenance was -6.50 which is significant at the .1 overall significance level. The t-value for the comparison of cost of 10 percent below the mean versus no preventive maintenance was 4.99 which was significant at the .1 overall significance level. As the difference in availability is a decrease and the difference in cost is an increase, this suggests that using scheduled replacement on components with a great deal of variance in the failure distribution would be of little practical use and detrimental to the availability of aircraft and more of a budgetary burden.

Twenty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 20 percent below the mean failure time and the actual failure time was a 2.43 percent ((64.43-62.86)/64.43) decrease. The percentage change in cost between replacing components at 20 percent below the mean failure time and the actual failure time was a 16.10 percent ((25,064,369-29,098,724)/25,064,369) increase. The t-value for the availability comparison was -2.42 and was not significant at the .1 overall significance level. The t-value for the cost comparison was 9.59 and was significant at the .1 overall significance level. Similar to the results with 10 percent below the mean and no preventive maintenance, the 20 percent comparison with no preventive maintenance results in higher cost and lower availability, but not significantly lower.

Thirty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 30 percent below the mean failure time and the actual failure time was a 2.32 percent ((64.43-62.93)/64.43) decrease and the percentage change in cost was a 26.82 percent ((25,064,369-31,787,372)/25,064,369) increase. The t-value for the comparison of availability was -11.42 and was significant at the .1 overall significance level. The t-value for the comparison of cost was 17.39 and was significant at the .1 overall significance level. Again, this suggests that using scheduled replacement on components with a failure distribution with a large variance (like the exponential distribution) leads to higher costs and lower availability. Based on these findings, replacing components with high failure variability at 10, 20, and 30 percent below the mean failure time are not prudent solutions when compared to no preventive maintenance.

Comparison of 10, 20, and 30 percent below the mean preventive maintenance policies. When the 10, 20, and 30 percent below the mean availability results were compared, only the 10 and 30 percent results were statistically different (t = 6.18) from each other at the .1 overall significance level. The costs associated with the three preventive maintenance policies were all significantly different at the .1 overall significance level. This information suggests that increasing levels of preventive maintenance create higher maintenance costs with little change in availability.

Erlang Distribution

A summary of the simulation results for the four Erlang distribution models is provided in appendix C. The averages for the 15 replications of each of the four models are reported in table 8.

Table 8
Erlang Distribution Overall Averages

	Availability (%)	Cost ($)
No PM	64.38	25,206,219
10 percent	67.49	22,197,000
20 percent	68.37	23,496,357
30 percent	68.82	26,478,496

A comparison of availability to cost implies that when component failure distributions have a moderate amount of variability, such as the Erlang distribution, scheduled replacement at 10 and 20 percent below the mean failure time tends to have decreased maintenance cost with increased availability. With replacement at 30 percent below the mean failure time, maintenance cost is higher but the availability is higher as well.

Availability paired difference tests results are reported in table 9 and cost paired difference tests results are reported in table 10.

Table 9
T-values for the Erlang Distribution Paired Difference Tests of Availability

	10 percent	20 percent	30 percent	No PM
10 percent	---	-2.92*	-5.54*	8.77*
20 percent	---	---	-1.72	13.93*
30 percent	---	---	---	21.23*

* Significant at the overall significance level of .1 (n = 15, df = 14, and critical t-value = 2.739)

Table 10
T-values for the Erlang Distribution Paired Difference Tests of Cost

	10 percent	20 percent	30 percent	No PM
10 percent	---	-5.76*	-15.02*	-11.35*
20 percent	---	---	-9.93*	-6.14*
30 percent	---	---	---	4.66*

* Significant at the overall significance level of .1 (n = 15, df = 14, and critical t-value = 2.739)

Ten percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 10 percent below the mean failure time and the actual failure time was a 4.83 percent ((64.38-67.49)/64.38) increase and the percentage change in cost was a 11.94 percent ((25,206,219-22,197,000)/25,206,219) decrease. The t-value for the comparison of availability of 10 percent below the mean versus no preventive maintenance was 8.77 which is significant at the .1 overall significance level. The t-value for the comparison of cost of 10 percent below the mean versus no preventive maintenance was -11.35 which was significant at the .1 overall significance level. These findings suggest that if components with a failure distribution with a moderate amount of variance, such as the Erlang distribution, are replaced at 10 percent below the mean failure time, the availability should increase and maintenance cost should decrease.

Twenty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 20 percent below the mean failure time and the actual failure time was a 6.2 percent ((64.38-68.37)/64.38) increase. The percentage change in cost between replacing components at 20 percent below the mean failure time and the actual failure time was a 6.78 percent ((25,206,219-

23,496,357)/25,206,219) decrease. The t-value for the availability comparison was 13.93 and was significant at the .1 overall significance level. The t-value for the cost comparison was -6.14 and was significant at the .1 overall significance level. Similar to the results with the comparison of 10 percent below the mean failure time and no preventive maintenance, the 20 percent comparison with no preventive maintenance results in lower cost and higher availability.

Thirty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 30 percent below the mean failure time and the actual failure time was a 6.89 percent ((64.38-68.82)/64.38) increase and the percentage change in cost was a 5.05 percent ((25,206,219-26,478,496)/25,206,219) increase. The t-value for the comparison of availability was 21.23 and was significant at the .1 overall significance level. The t-value for the comparison of cost was 4.66 and was significant at the .1 overall significance level. This suggests that scheduled replacement at 30 percent below the mean failure time on components with a failure distribution with a moderate amount of variance (like the Erlang distribution) leads to higher availability but also higher maintenance cost. Based on these findings, when compared to no preventive maintenance, replacing components with moderate failure variability at 10, 20, and 30 percent below the mean failure time are worthy solutions in terms of availability in all three policies and in terms of cost in the 10 and 20 percent policies.

Comparison of 10, 20, and 30 percent below the mean preventive maintenance policies. When the 10, 20, and 30 percent below the mean availability results were compared, only the 20 and 30 percent results appeared statistically no different ($t = -1.72$)

at the .1 overall significance level. The costs associated with the three preventive maintenance policies were all significantly different at the .1 overall significance level. The percentage change in availability between replacing components at 20 percent below the mean failure time and 30 percent below the mean failure time was a .65 percent ((68.37-68.82)/68.37) increase and the percentage change in cost was a 12.69 percent ((23,496,357-26,478,496)/23,496,357) increase. Therefore, a .65 percent increase in availability requires a 12.69 percent increase in cost. These findings suggest that a 20 percent below the mean scheduled replacement policy is more cost effective than the 30 percent below the mean scheduled replacement policy when there is moderate variance in the component's failure distribution.

Normal Distribution

A summary of the simulation results for the four normal distribution models is provided in appendix D. The averages for the 15 replications of each of the four models are reported in table 11.

Table 11
Normal Distribution Overall Averages

	Availability (%)	Cost ($)
No PM	64.46	25,200,156
10 percent	77.44	11,297,926
20 percent	81.84	12,838,070
30 percent	81.58	19,604,247

A comparison of availability to cost implies that when component failure distributions have a small amount of variability, such as the normal (μ, 0.1μ) distribution, scheduled

replacement appears to offer higher percentages of availability and lower levels of maintenance cost.

Availability paired difference tests results are reported in table 12 and cost paired difference tests results are reported in table 13.

Table 12
T-values for the Normal Distribution Paired Difference Tests of Availability

	10 percent	20 percent	30 percent	No PM
10 percent	---	-16.63*	-17.27*	41.44*
20 percent	---	---	2.89*	104.43*
30 percent	---	---	---	90.64*

* Significant at the overall significance level of .1 (n = 15, df = 14, and critical t-value = 2.739)

Table 13
T-values for the Normal Distribution Paired Difference Tests of Cost

	10 percent	20 percent	30 percent	No PM
10 percent	---	-9.00*	-53.83*	-48.58*
20 percent	---	---	-98.35*	-48.21*
30 percent	---	---	---	-19.05*

* Significant at the overall significance level of .1 (n = 15, df = 14, and critical t-value = 2.739)

Ten percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 10 percent below the mean failure time and the actual failure time was a 20.14 percent ((64.46-77.77)/64.46) increase. The percentage change in cost between replacing components at 10 percent below the mean failure time and the actual failure time was a 55.17 percent ((25,200,156-11,297,926)/25,200,156) decrease. The t-value for the comparison of availability of 10 percent below the mean failure time versus no preventive maintenance was 41.44 which is significant at the .1 overall significance level. The t-value for the comparison of cost

of 10 percent below the mean versus no preventive maintenance was –48.58 which was significant at the .1 overall significance level. These findings suggest that if components with a failure distribution with a small amount of variance, such as the normal distribution, are replaced at 10 percent below the mean failure time, the availability should increase and maintenance cost should decrease considerably.

Twenty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 20 percent below the mean failure time and the actual failure time was a 26.97 percent ((64.46-81.84)/64.46) increase. The percentage change in cost between replacing components at 20 percent below the mean failure time and the actual failure time was a 49.06 percent ((25,200,156-12,838,070)/25,200,156) decrease. The t-value for the availability comparison was 104.43 and was significant at the .1 overall significance level. The t-value for the cost comparison was –48.21 and was significant at the .1 overall significance level. Similar to the results with 10 percent below the mean failure time and no preventive maintenance, the 20 percent comparison with no preventive maintenance results in much cost and significantly higher availability.

Thirty percent below the mean compared to no preventive maintenance. The percentage change in availability between replacing components at 30 percent below the mean failure time and the actual failure time was a 26.55 percent ((64.46-81.58)/64.46) increase and the percentage change in cost was a 22.21 percent ((25,200,156-19,604,247)/25,200,156) decrease. The t-value for the comparison of availability was 90.64 and was significant at the .1 overall significance level. The t-value for the comparison of cost was –19.05 and was significant at the .1 overall significance level.

Again, this suggests that using scheduled replacement on components with a failure distribution with a tight variance (like the normal distribution) leads to lower costs and higher availability. Based on these findings, replacing components with low failure variability at 10, 20, and 30 percent below the mean failure time appears to be a reasonable solution when compared to no preventive maintenance.

Comparison of 10, 20, and 30 percent below the mean preventive maintenance policies. When the 10, 20, and 30 percent below the mean availability results were compared, all appeared to be statistically different at the .1 overall significance level (see table 11). The costs associated with the three preventive maintenance policies were all significantly different at the .1 overall significance level (see table 12). The percentage change in availability between replacing components at 20 percent below the mean failure time and 30 percent below the mean failure time was a .33 percent ((81.84-81.58)/81.84)) decrease and the percentage change in cost was 52.70 percent ((12,838,070-19,604,247)/12,838,070) increase. Therefore, a 52.70 percent increase in cost caused a .33 percent decrease in availability. These findings suggest that a 20 percent below the mean scheduled replacement policy is more cost effective than the 30 percent below the mean scheduled replacement policy when there is a small amount of variance in the component's failure distribution.

Analysis

This study set out to answer three questions about the effects of preventive maintenance on availability and maintenance cost. The first question was:

> By using a scheduled replacement maintenance approach for the nine components, will availability increase?

The findings suggest that if the variance in the components' failure distributions is moderate or small (as in the Erlang and normal distributions, respectively) then availability will increase. As demonstrated by the normal distribution, a tighter variance offers the best results in terms of increasing the availability. If the variance is large as in the exponential distribution, then increasing levels of preventive maintenance appear to have a negative effect on availability.

The second question concerning the effects of preventive maintenance was:

> By using a scheduled replacement maintenance approach for the nine components, will maintenance cost decrease?

The findings suggest that if there is great deal of variance in the components' failure distributions, as demonstrated with the exponential distribution, then preventive maintenance at 10, 20, and 30 percent below the mean will result in higher levels of maintenance cost compared to no preventive maintenance. If the variance in the components' failure distribution is moderate, as demonstrated with Erlang distribution, then maintenance cost will decrease up to 20 percent below the mean failure time and increase at 30 percent below the mean failure time when compared to no preventive maintenance. If the variance is small, as demonstrated with the normal distribution, then preventive maintenance at 10, 20, and 30 percent below the mean appears to result in lower maintenance cost.

The third question concerning the effects of preventive maintenance was:

> What is the cost comparison of the changes in availability and maintenance cost?

There appears to be a point of diminishing return where higher levels of preventive maintenance have caused availability to increase at a slower rate with maintenance cost increasing at a faster rate. In both the normal and Erlang distributions, the point of diminishing return appears to be at 20 percent below the mean. When comparing scheduled replacement at 20 percent below the mean to 30 percent below the mean, a significant increase in maintenance cost causes only a slight increase in availability. For the exponential distribution with high variance, the cost increases while the availability decreases.

V. Conclusion

Overview

This study identified the potential effects of increased use of scheduled replacement of components with failure distributions under three different levels of variance (high, moderate, and low). This chapter will present a summary of the study's findings, discuss the study's limiting factors, and provide suggestions for future research.

Discussion

High Variance in Failure Distribution. This research effort demonstrated that when components have failure distributions with a high degree of variance, like the exponential distribution, scheduled replacement appears to have a deleterious effect on both availability and maintenance cost. When compared to no preventive maintenance, scheduled replacement at 10, 20, and 30 percent below the mean failure time achieved lower percentages of availability (decreases of 1.44, 2.43, and 2.32 percent, respectively) and increased cost (6.78, 16.10, and 26.82 percent, respectively). Therefore, these findings suggest that scheduled replacement of components with failure distributions with high variance would only have negative effects on availability and cost. Components that have failure distributions with a high variance could benefit from a thorough analysis of their inherent reliability by their manufacturer. The proper course of action may be modification or replacement.

Moderate Variance in Failure Distribution. This study showed that when components have failure distributions with a moderate degree of variance, like the Erlang distribution, scheduled replacement appears to have a positive effect up to a point.

Maintenance cost was lower and availability was higher under scheduled replacement policies at 10 and 20 percent below the mean failure time when compared to no preventive maintenance. The 20 percent below the mean scheduled replacement policy had lower maintenance cost and higher availability than the 10 percent below the mean policy. The 30 percent below the mean scheduled replacement policy had higher availability than the no preventive maintenance policy but was only marginally better (.65 percent) than the 20 percent replacement policy. However, this increased availability was at a significant cost (increase of 12.69 percent) when compared to the availability recognized by the 20 percent below the mean scheduled replacement policy. Scheduled replacement at levels greater than 20 percent below the mean failure time appears to achieve only slight increases in availability with large increases in cost.

Low Variance in Failure Distribution. This investigation showed that when components have failure distributions with a small degree of variance, like the normal (μ, 0.1μ) distribution, scheduled replacement appears to be superior to no preventive maintenance, in both cost and availability, when replacement occurs at 10, 20, and 30 percent below the mean. The relationship between scheduled replacement and no preventive maintenance in a situation with little variance is as expected because failure times are now highly predictable and preventive maintenance has a high probability of avoiding failure. Using preventive maintenance in conjunction with the small confidence intervals resulting from the low variance will limit the number of failures in the left tail of the curve. Scheduled replacement at levels past 20 percent below the mean appear to have negative effects on availability, however. Although still significantly cheaper than no preventive maintenance, the availability achieved with scheduled replacement at 30

percent below the mean failure time was .33 percent lower than scheduled replacement at 20 percent below the mean failure time and cost 52.70 percent more. Scheduled replacement at levels greater than 20 percent below the mean failure time appears to have a negative effect on availability with increasing levels of cost.

Limitations

There are two primary limitations to this research effort and two limitations to the concept of increased scheduled maintenance. The first is the unavailability of actual failure time and repair time information. Because of this lack of information, failure time distributions were estimated. To overcome this limitation, several different distributions were used and analysis was performed to determine the robustness of the results. The mean time to repair of each component was used as a constant.

The second limitation is the accuracy of the information in the G081 computer system. A 1991 research study suggested that the majority of input errors are accidental and most likely the result of inadequate training and "non-user friendly" data collection environment (Determan, 1991:71-72). A 1994 Department of Transportation report demonstrates that the problem is still apparent. This report stated that there is a problem with apathy because mechanics do not see a benefit from correctly entering the data (DOT, 1994:12). Since that time changes were made to correct the inadequacies. However, it has only served to change the flavor of the input errors. Maintenance data is recorded by mechanics, then input into the G081 computer database by another person. Maintenance actions are recorded by a work unit code (WUC), which is a five digit alphanumeric code assigned to replaceable parts on an aircraft. Not understanding the

ramifications of their actions, mechanics are often not very careful about the accuracy of the information they report. It is not at all uncommon for mechanics to choose the first code in the WUC manual (11AAA) to document their activities (Weber, 1997:n. pag.). Reducing the number of WUCs is not a good solution, since historically, even when the correct WUC is available, mechanics often do not take the time to find it (DOT, 1994:19).

A possible limitation to the concept of increased scheduled maintenance is the lack of spare parts. A 1995 Government Accounting Office report stated that "in recent years, between one-quarter and one-half of the C-5 total not mission capable time was due to the lack of spare parts" (GAO, 1995:2). If spare parts are lacking under the current system, then attempting to replace components early could exacerbate the problem of the scarcity of spare parts. However, the use of more scheduled replacement could be a partial solution to the lack of spare parts. Flying hours are scheduled, for the most part, well in advance of when they are actually flown. With scheduled replacement, forecasting should be more accurate because uncertainty is reduced. If the forecasting is more accurate, then safety stock and spares levels could possibly be reduced. Therefore, scheduled replacement of components could result in a reduction in spares levels and subsequently a reduction in the shortage of spares through the use of a "just-in-time" type of replenishment and allow batch type ordering as opposed to one at a time.

Cannibalization could further hinder the application of increased scheduled maintenance. Cannibalization is defined as removing functional components from an aircraft that is classified not mission capable and installing on these on another aircraft to make it mission capable (HQ USAF, 1997:42). Actions such as these will make

establishing the appropriate replacement time difficult. Cannibalization has a tendency to "decrease the life expectancy of aircraft systems and consumes vast amounts of labor that could be better employed elsewhere" (GAO, 1995:5). However, increased use of scheduled replacement could decrease the necessity of cannibalization. If components are replaced based on age (flying hours), then unexpected failures are reduced and cannibalization should become increasingly unnecessary.

Recommendations for Future Research

The greatest limitations of this study were the lack of actual fail times and the potential for inaccurate data in the G081 computer system. The C-141 System Program Management Directorate is performing a similar study. Their work-around was to create a web browser based input screen for the components they are reviewing. The maintenance controller inputs the appropriate data into G081 and then logs onto the internet page through their web browser and inputs some of the same information into that screen (Wrigley, 1998:n. pag.). They believe this provides them with accurate information on the components they are studying. A similar approach could be applied to looking at C-5 components. However, if the people are not entering accurate data into G081, then the information entered into the web based system may be suspect as well. This method requires buy-in from personnel at all echelons to ensure the integrity of the information collected. The importance should be thoroughly explained perhaps through formal training.

Another suggestion would be to take a closer look at how increased use of preventive maintenance would affect spares levels. Such a study could also look at determining what the appropriate spares level should be.

Finally, there are other costs that could be factored into the cost equations used in this study. For example, the cost of shipping components should decrease because expedited transportation is used when aircraft break off-station. The cost of spares could be a factor, as well. If the use of preventive maintenance makes forecasting the need for spares more accurate then fewer would have to be kept on the shelf tying up critical budget dollars.

Conclusions

The findings of this study suggest that the level of variance in the failure distribution of components will have an affect on the effectiveness of a preventive maintenance program. The use of preventive maintenance on components with a high variance in the failure distribution appears to have a negative effect on availability at a higher cost than with not using preventive maintenance. The use of preventive maintenance on components with a moderate or small amount of variance in its failure distribution appears to be effective up to a point of diminishing return.

Appendix A: Maintenance Repair Team Information from Travis AFB from 1 Oct 1997 - 21 July 1998

MRT Report from 60 AGS - Travis AFB

Date	Cost	Location
9-Oct-97	$548	Yokota AB Japan
9-Oct-97	$2,128	Hill AFB UT
10-Oct-97	$2,256	Elmendorf AFB AK
25-Oct-97	$1,688	El Toro MCAS CA
29-Oct-97	$2,288	Anderson AB Guam
29-Oct-97	$598	El Centro NAS CA
31-Oct-97	$2,008	Buckley CO
1-Nov-97	$1,760	Cairo West
7-Nov-97	$1,228	Wright-Patterson AFB
7-Nov-97	$1,628	Wright-Patterson AFB
8-Nov-97	$1,940	Wright-Patterson AFB
9-Nov-97	$2,855	Dyess AFB TX
9-Nov-97	$1,214	Dyess AFB TX
10-Nov-97	$660	Mather AFB CA
11-Nov-97	$4,137	Elmendorf AFB AK
14-Nov-97	$0	Amendment
14-Nov-97	$1,027	North Ireland NAS CA
15-Nov-97	$550	McClellan AFB CA
16-Nov-97	$1,903	Nellis AFB NV
18-Nov-97	$121	Amendment
20-Nov-97	$710	Victorville CA
1-Dec-97	$1,499	Yokota AB Japan
17-Dec-97	$1,056	Hickam AFB HI
29-Dec-97	$3,420	Holloman AFB NM
30-Dec-97	$987	Elmendorf AFB AK
1-Jan-98	$924	Holloman AFB NM
15-Jan-98	$1,244	Hill AFB UT
16-Jan-98	$5,340	Buckley CO
17-Jan-98	$928	Ellington AFB TX
18-Jan-98	$5,152	Colorado Springs CO
18-Jan-98	$5,340	Amendment
23-Jan-98	$2,400	Panama City Panama
30-Jan-98	$5,360	Japan
8-Feb-98	$1,882	Eglin AFB FL
11-Feb-98	$1,866	Los Angelos International
20-Feb-98	$855	Hickam AFB HI
21-Feb-98	$811	Dover AFB DE
24-Feb-98	$1,700	Eilson AFB AK
3-Mar-98	$1,730	McChord AFB WA
7-Mar-98	$1,146	Eilson AFB AK
10-Mar-98	$3,480	Cannon AFB NM
12-Mar-98	$1,210	Edwards AFB CA
20-Mar-98	$8,740	Edwards AFB CA
25-Mar-98	$1,544	North Island CA
28-Mar-98	$1,470	Moffett Field CA
28-Mar-98	$1,042	Forbes field KS
30-Mar-98	$735	Moffett Field CA
30-Mar-98	$1,470	Moffett Field CA
3-Apr-98	$850	Yuma Az
5-Apr-98	$1,510	El Toro MCAS CA
9-Apr-98	$5,730	Classified
22-Apr-98	$898	not listed
28-Apr-98	$1,458	Nellis AFB NV
2-May-98	$2,591	Thailand
2-May-98	$6,480	Berlin, Germany
2-May-98	$1,510	Davis-Monthan AFB AZ
2-May-98	$2,640	Nellis AFB NV
5-May-98	$1,971	Luke AFB AZ
19-May-98	$2,116	not listed
19-May-98	$1,072	Ft Cambell KY
27-May-98	$1,423	Colorado Springs CO
28-May-98	$1,639	not listed
7-Jun-98	$6,703	not listed
7-Jun-98	$2,814	Eilson AFB AK
9-Jun-98	$1,986	Nellis AFB NV
10-Jun-98	$1,208	Holloman AFB NM
14-Jun-98	$1,155	Portland OR
22-Jun-98	$731	March AFB

MRT Report from 60 EMS - Travis AFB

Date	Number of Days	Cost	Location
4-Oct-97	14	$4,172	Yokota AB Japan
5-Oct-97	10	$3,800	Yokota AB Japan
10-Oct-97	10	$1,130	Yokota AB Japan
11-Oct-97	10	$1,870	Yokota AB Japan
13-Oct-97	10	$1,260	Yokota AB Japan
23-Oct-97	10	$1,470	Utaphio, Thailand
31-Oct-97	10	$850	Whiteman AFB MO
10-Nov-97	1	$88	Nellis AFB NV
11-Nov-97	10	$510	Pago Pago, Western Samoa
16-Nov-97	10	$740	Mather AFB CA
28-Nov-97	10	$1,210	Khorai, Thailand
30-Nov-97	10	$1,100	Los Alamedos CA
6-Dec-97	10	$1,070	Eilson AFB AK
22-Dec-97	10	$1,370	Iwakuni, Japan
31-Dec-97	10	$1,410	Kadena AB Japan
10-Jan-98	14	$4,788	Hill AFB UT
15-Jan-98	10	1220	Hickam AFB HI
17-Jan-98	10	3780	Hickam AFB HI
17-Jan-98	10	1260	Hickam AFB HI
17-Jan-98	10	$3,400	Hill AFB UT
19-Jan-98	5	800	Hickam AFB HI
31-Jan-98	10	1440	Elmendorf AFB AK
31-Jan-98	10	1880	Elmendorf AFB AK
3-Feb-98	10	910	Buckley Field CO
6-Feb-98	10	2740	Colorado Springs CO
7-Feb-98	2	160	Beale AFB CA
9-Feb-98	10	1300	Fajarah, UAE
23-Feb-98	10	1370	Buckley Field CO
20-Apr-98	10	7360	Davis Field OK
27-May-98	10	1180	Fort Alliance TX
10-Jun-98	10	1601	Anderson AB Guam
10-Jun-98	10	2855	Elmendorf AFB AK
5-Jul-98	10	2280	Elmendorf AFB AK

Average Cost:	$2,005
Average Number of Days:	9.58
Number of MRT deployments:	112
Number of C-5 Flights:	1939
Percentage Requiring MRT:	5.8%

Source: MRT and Flight information from 1 Oct 97 - 21 July From HQ AMC/LGA

Appendix B: Summary Results of the Four Exponential Distribution Models

10 Percent Below the Mean

Replication	Availability	Cost
1	62.56%	$ 24,833,165
2	63.60%	$ 26,141,184
3	63.08%	$ 25,019,052
4	63.07%	$ 25,725,045
5	63.68%	$ 29,823,974
6	63.69%	$ 28,840,021
7	65.04%	$ 20,413,561
8	64.07%	$ 28,202,673
9	62.93%	$ 26,411,542
10	63.65%	$ 27,910,683
11	63.14%	$ 26,244,458
12	64.32%	$ 28,126,034
13	63.12%	$ 25,754,831
14	63.87%	$ 30,530,544
15	63.77%	$ 26,592,712
16	63.63%	$ 25,999,656
17	63.86%	$ 27,959,266
18	64.96%	$ 28,535,477
19	64.09%	$ 27,561,595
20	63.49%	$ 27,559,764
21	62.68%	$ 26,302,140
22	63.28%	$ 25,471,031
23	62.24%	$ 25,838,430
24	63.85%	$ 26,146,380
25	62.90%	$ 25,466,444
26	62.27%	$ 26,456,026
27	63.81%	$ 27,910,317
28	64.42%	$ 27,684,371
29	63.56%	$ 26,735,549
30	62.50%	$ 26,729,105

20 Percent Below the Mean

Replication	Availability	Cost
1	62.55%	$ 26,674,799
2	63.12%	$ 27,877,068
3	63.44%	$ 29,498,815
4	62.08%	$ 30,479,454
5	63.93%	$ 30,977,387
6	45.89%	$ 30,232,918
7	63.29%	$ 29,242,960
8	63.59%	$ 27,081,272
9	62.45%	$ 33,751,822
10	63.56%	$ 29,808,176
11	63.91%	$ 29,412,064
12	64.15%	$ 29,529,244
13	62.96%	$ 31,006,992
14	62.94%	$ 27,657,783
15	63.84%	$ 29,946,917
16	62.47%	$ 28,758,764
17	62.28%	$ 30,417,906
18	64.57%	$ 30,713,795
19	64.01%	$ 29,883,034
20	64.03%	$ 30,254,901
21	62.21%	$ 26,196,600
22	63.40%	$ 30,628,060
23	63.39%	$ 28,853,815
24	61.89%	$ 25,591,001
25	65.31%	$ 23,507,382
26	65.70%	$ 29,286,253
27	63.26%	$ 28,089,879
28	64.45%	$ 29,024,280
29	63.59%	$ 28,854,428
30	63.63%	$ 29,723,964

30 Percent Below the Mean

Replication	Availability	Cost
1	62.17%	$ 29,569,656
2	63.20%	$ 31,803,270
3	62.89%	$ 31,876,171
4	62.25%	$ 32,321,918
5	62.65%	$ 32,455,383
6	62.48%	$ 31,295,355
7	63.72%	$ 33,869,845
8	63.15%	$ 31,042,607
9	63.53%	$ 33,199,782
10	62.88%	$ 30,567,953
11	63.54%	$ 32,050,393
12	62.41%	$ 32,721,885
13	62.94%	$ 30,946,017
14	62.96%	$ 36,925,909
15	63.34%	$ 31,975,692
16	62.56%	$ 31,066,751
17	63.20%	$ 30,986,607
18	64.31%	$ 33,874,783
19	63.99%	$ 32,343,871
20	62.89%	$ 32,650,499
21	62.46%	$ 29,794,144
22	62.27%	$ 29,879,512
23	61.80%	$ 30,306,986
24	63.32%	$ 32,343,912
25	62.71%	$ 31,028,498
26	61.42%	$ 26,818,252
27	63.51%	$ 32,533,730
28	64.15%	$ 33,842,847
29	63.43%	$ 32,631,006
30	61.90%	$ 30,897,929

No Preventive Maintenance

Replication	Availability	Cost
1	63.46%	$ 25,501,910
2	64.22%	$ 24,473,262
3	63.33%	$ 22,738,597
4	64.22%	$ 23,999,124
5	64.77%	$ 26,799,427
6	65.63%	$ 24,364,831
7	63.62%	$ 23,970,270
8	64.59%	$ 27,926,902
9	64.92%	$ 26,377,485
10	64.33%	$ 27,443,243
11	64.32%	$ 25,193,337
12	64.42%	$ 26,517,135
13	64.54%	$ 24,589,380
14	64.61%	$ 24,231,771
15	65.92%	$ 25,337,039
16	63.74%	$ 25,113,222
17	64.63%	$ 26,869,329
18	65.39%	$ 24,907,731
19	65.29%	$ 25,177,005
20	64.64%	$ 24,088,403
21	63.03%	$ 22,341,593
22	64.08%	$ 25,478,918
23	63.72%	$ 23,067,065
24	64.14%	$ 23,728,332
25	65.71%	$ 25,939,103
26	63.41%	$ 23,095,998
27	63.99%	$ 27,322,060
28	65.96%	$ 26,435,508
29	64.70%	$ 25,373,959
30	63.64%	$ 23,529,139

Appendix C: Summary Results of the Four Erlang Distribution Models

10 Percent Below the Mean

Replication	Availability	Cost
1	67.38%	$ 22,369,758
2	66.92%	$ 22,128,572
3	68.61%	$ 22,073,156
4	66.73%	$ 21,406,565
5	67.74%	$ 23,706,089
6	67.12%	$ 21,808,911
7	69.49%	$ 22,422,175
8	66.89%	$ 22,134,857
9	67.86%	$ 23,145,588
10	68.08%	$ 22,605,185
11	67.92%	$ 22,233,697
12	65.64%	$ 22,459,036
13	68.19%	$ 22,476,275
14	66.91%	$ 21,412,694
15	66.91%	$ 20,572,438

20 Percent Below the Mean

Replication	Availability	Cost
1	68.25%	$ 23,842,669
2	67.34%	$ 23,841,048
3	68.64%	$ 22,151,106
4	67.80%	$ 22,660,350
5	67.55%	$ 23,754,279
6	69.37%	$ 23,459,028
7	68.79%	$ 23,360,448
8	68.64%	$ 23,920,420
9	67.24%	$ 23,572,630
10	68.61%	$ 23,968,177
11	70.12%	$ 25,425,819
12	68.82%	$ 23,124,879
13	68.96%	$ 24,547,898
14	68.85%	$ 23,711,260
15	66.63%	$ 21,105,337

30 Percent Below the Mean

Replication	Availability	Cost
1	68.90%	$ 26,807,404
2	68.22%	$ 25,787,091
3	68.94%	$ 25,616,410
4	69.10%	$ 27,019,051
5	68.96%	$ 25,860,768
6	68.91%	$ 26,093,943
7	68.72%	$ 26,815,840
8	69.41%	$ 27,588,729
9	68.89%	$ 27,065,585
10	68.23%	$ 27,046,737
11	68.68%	$ 26,460,690
12	68.22%	$ 24,813,881
13	69.78%	$ 27,307,112
14	68.44%	$ 25,999,269
15	68.93%	$ 26,894,925

No Preventive Maintenance

Replication	Availability	Cost
1	63.61%	$ 25,547,094
2	64.18%	$ 25,215,732
3	63.10%	$ 23,801,237
4	65.19%	$ 25,739,982
5	65.63%	$ 26,392,474
6	63.80%	$ 24,074,038
7	64.19%	$ 24,312,097
8	64.96%	$ 26,822,055
9	63.29%	$ 26,324,846
10	63.86%	$ 23,740,274
11	64.71%	$ 25,208,515
12	64.80%	$ 24,776,686
13	65.93%	$ 26,500,444
14	64.84%	$ 25,564,731
15	63.67%	$ 24,073,072

Appendix D: Summary Results of the Four Normal Distribution Models

10 Percent Below the Mean

Replication	Availability	Cost
1	78.13%	$ 11,322,245
2	76.63%	$ 11,949,539
3	78.37%	$ 10,299,673
4	76.02%	$ 10,605,667
5	77.38%	$ 12,056,451
6	77.41%	$ 10,995,486
7	78.15%	$ 12,338,642
8	79.08%	$ 11,229,536
9	76.50%	$ 10,858,797
10	77.19%	$ 11,382,981
11	75.57%	$ 11,485,487
12	78.14%	$ 10,757,879
13	78.13%	$ 12,153,228
14	77.41%	$ 11,235,732
15	77.54%	$ 10,797,551

20 Percent Below the Mean

Replication	Availability	Cost
1	82.34%	$ 12,393,949
2	82.33%	$ 12,769,976
3	81.55%	$ 12,034,234
4	82.06%	$ 12,569,407
5	82.85%	$ 12,768,013
6	81.82%	$ 12,775,825
7	82.08%	$ 12,331,590
8	82.34%	$ 12,559,919
9	81.85%	$ 12,725,418
10	80.57%	$ 12,466,929
11	82.11%	$ 12,904,691
12	81.60%	$ 12,136,252
13	81.84%	$ 12,838,070
14	82.37%	$ 12,426,422
15	81.85%	$ 12,316,613

30 Percent Below the Mean

Replication	Availability	Cost
1	81.62%	$ 19,566,533
2	81.62%	$ 19,638,462
3	81.62%	$ 19,645,268
4	81.37%	$ 19,471,582
5	81.60%	$ 19,643,711
6	81.62%	$ 19,603,683
7	81.61%	$ 19,654,275
8	81.61%	$ 19,578,813
9	81.39%	$ 19,596,271
10	81.64%	$ 19,653,154
11	81.63%	$ 19,604,533
12	81.64%	$ 19,559,551
13	81.39%	$ 19,534,754
14	81.64%	$ 19,670,575
15	81.64%	$ 19,642,539

No Preventive Maintenance

Replication	Availability	Cost
1	63.86%	$ 25,578,531
2	64.30%	$ 25,063,984
3	63.54%	$ 23,294,513
4	65.17%	$ 26,075,524
5	65.31%	$ 26,579,677
6	63.82%	$ 23,900,997
7	63.80%	$ 24,270,546
8	65.16%	$ 26,259,521
9	64.82%	$ 25,966,863
10	63.82%	$ 23,990,778
11	64.48%	$ 25,491,927
12	64.79%	$ 26,211,858
13	65.50%	$ 26,501,408
14	64.84%	$ 25,056,370
15	63.70%	$ 23,759,848

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Vita

Captain William T. Webb was born on 8 May 1971 in Deming, New Mexico. He graduated from Skyline High School in Dallas, Texas in 1989. He entered Texas A&M University and the Texas A&M Corps of Cadets in August 1989. Upon graduation in May of 1994, he earned a Bachelor of Science Degree in Political Science.

He was commissioned through the Reserve Officer Training Corps in May 1994 and entered active duty in the Air Force in September 1994 with an assignment to Edwards AFB, California. He completed Undergraduate Transportation Officer's School in February 1995 as an Honor Graduate. At Edwards, he held the positions of Vehicle Maintenance Officer and Combat Readiness Flight Commander.

He was selected to attend the Air Force Institute of Technology and will receive a Master of Science Degree in Transportation Management upon graduation. Following graduation, he will be assigned as Chief of Transportation at Headquarters, 8th Air Force, Barksdale AFB, Louisiana.

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13. ABSTRACT *(Maximum 200 Words)*

The C-5 consistently performs below its established mission capable rate of 75 percent. The purpose of this study was to investigate whether or not mission capable rates and maintenance costs can be improved by increased use of scheduled maintenance.

Nine C-5 components were studied. Availability and cost were compared when scheduled replacement occurred at ten, twenty, and thirty percent before their respective mean time between failure and actual failure times. Actual failure times were not available so they were generated using simulation. The trade-off of using preventive maintenance is the decreased cost of sending fewer maintenance repair teams and increased C-5 availability, versus the increased cost of early component replacement.

This study's findings suggest that the level of variance in the failure distribution of components will have an influence on the effectiveness of a preventive maintenance program. The use of preventive maintenance on components with a high variance in the failure distribution appears to have a negative effect on availability at a higher cost than with not using preventive maintenance. The use of preventive maintenance on components with a moderate or small amount of variance in its failure distribution appears to be effective up to a point of diminishing return.

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